Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **409,** 1585–1593 (2010) doi:10.1111/j.1365-2966.2010.17401.x

# Flavours of variability: 29 RR Lyrae stars observed with *Kepler*

J. M. Benkő,[1⋆] K. Kolenberg,[2] R. Szabó,[1] D. W. Kurtz,[3] S. Bryson,[4] J. Bregman,[4] M. Still,[4] R. Smolec,[2] J. Nuspl,[1] J. M. Nemec,[5] P. Moskalik,[6] G. Kopacki,[7] Z. Kolláth,[1] E. Guggenberger,[2] M. Di Criscienzo,[8] J. Christensen-Dalsgaard,[9] H. Kjeldsen,[9] W. J. Borucki,[4] D. Koch,[4] J. M. Jenkins[10] and J. E. Van Cleve[10]

[1]*Konkoly Observatory, H-1525 Budapest, PO Box 67, Hungary*
[2]*Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180 Vienna, Austria*
[3]*Jeremiah Horrocks Institute of Astrophysics, University of Central Lancashire, Preston PR1 2HE*
[4]*NASA Ames Research Center, MS 244-30, Moffett Field, CA 94035, USA*
[5]*Department of Physics & Astronomy, Camosun College, Victoria, BC V8P 5J2, Canada*
[6]*Copernicus Astronomical Centre, ul. Bartycka 18, 00-716 Warsaw, Poland*
[7]*Instytut Astronomiczny Uniwersytetu Wrocławskiego, Kopernika 11, 51-622 Wrocław, Poland*
[8]*INAF-Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monte Porzio Catone, Italy*
[9]*Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*
[10]*SETI Institute/NASA Ames Research Center, MS 244-30, Moffett Field, CA 94035, USA*

Accepted 2010 July 22. Received 2010 July 21; in original form 2010 June 4

## ABSTRACT

We present our analysis of *Kepler* observations of 29 RR Lyrae stars, based on 138 d of observation. We report precise pulsation periods for all stars. Nine of these stars had incorrect or unknown periods in the literature. 14 of the stars exhibit both amplitude and phase Blazhko modulations, with Blazhko periods ranging from 27.7 to more than 200 d. For V445 Lyr, a longer secondary variation is also observed in addition to its 53.2-d Blazhko period. The unprecedented precision of the *Kepler* photometry has led to the discovery of the the smallest modulations detected so far. Moreover, additional frequencies beyond the well-known harmonics and Blazhko multiplets have been found. These frequencies are located around the half-integer multiples of the main pulsation frequency for at least three stars. In four stars, these frequencies are close to the first and/or second overtone modes. The amplitudes of these periodicities seem to vary over the Blazhko cycle. V350 Lyr, a non-Blazhko star in our sample, is the first example of a double-mode RR Lyrae star that pulsates in its fundamental and second overtone modes.

**Key words:** stars: oscillations – stars: variables: RR Lyrae.

## 1 INTRODUCTION

The ultraprecise photometry by the *Kepler* space telescope opens up the possibility of discovering new phenomena and shedding new light on long-standing astrophysical problems (Gilliland et al. 2010). One of the most interesting unsolved problems is the physical origin of the Blazhko (1907) effect, an amplitude and/or phase modulation of RR Lyrae stars. The leading explanations are as follows:

(1) an oblique rotator model that invokes a magnetic field (Shibahashi 2000);

(2) a model with resonant coupling between radial and non-radial mode(s) (Dziembowski & Mizerski 2004);

(3) a mechanism invoking a cyclic variation of the turbulent convection caused by a transient magnetic field (Stothers 2006).

At present none of these models explains all the observed properties of stars showing the Blazhko effect. It is not even clear whether a modification of the above ideas or new astrophysical processes are needed to solve the problem. Comprehensive discussions of the observational and theoretical properties of Blazhko RR Lyrae stars are given by Szeidl (1988) and Kovács (2009).

This paper describes new properties of RR Lyrae stars revealed by early data from the *Kepler* photometer. Here we concentrate on the results based mostly on Fourier analyses. A detailed study of all observed stars is beyond the scope of this paper.

## 2 DATA

A detailed technical description of the *Kepler Mission* can be found in Koch et al. (2010) and Jenkins et al. (2010a,b). At the time of writing this paper three long-cadence (29.4-min integration time) photometric data sets have been released to the *Kepler* Asteroseismic Science Consortium (KASC). Altogether

⋆E-mail: benko@konkoly.hu

**Table 1.** Basic parameters of 29 RR Lyrae stars observed by *Kepler* (long cadence) during the runs from Q0 to Q2.

| KIC | RA (J 2000) | Dec. (J 2000) | $K_p$ (mag) | $P_0$ (d) | $\sigma(P_0)$ ($10^{-5}$ d) | $A_1$ (mag) | $\sigma(A_1)$ ($10^{-3}$ mag) | ID | Runs | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| 3733346 | 19 08 27.23 | +38 48 46.19 | 12.684 | 0.682 04 | 1.68 | 0.266 | 2.2 | NR Lyr | Q1, Q2 | |
| 3864443 | 19 40 06.96 | +38 58 20.35 | 15.593 | 0.486 80 | 0.73 | 0.331 | 2.4 | V2178 Cyg | Q1, Q2 | Bl, n |
| 3866709 | 19 42 08.00 | +38 54 42.30 | 16.265 | 0.470 71 | 0.85 | 0.340 | 3.0 | V715 Cyg | Q1, Q2 | |
| 4484128 | 19 45 39.02 | +39 30 53.42 | 15.363 | 0.547 87 | 1.24 | 0.299 | 2.9 | V808 Cyg | Q1, Q2 | Bl |
| 5299596 | 19 51 17.00 | +40 26 45.20 | 15.392 | 0.523 64 | 0.91 | 0.195 | 1.5 | V782 Cyg | Q1, Q2 | |
| 5559631 | 19 52 52.74 | +40 47 35.45 | 14.643 | 0.620 72 | 1.48 | 0.273 | 2.4 | V783 Cyg | Q1, Q2 | Bl |
| 6070714 | 19 56 22.91 | +41 20 23.53 | 15.370 | 0.534 10 | 0.93 | 0.229 | 1.7 | V784 Cyg | Q1, Q2 | |
| 6100702 | 18 50 37.73 | +41 25 25.72 | 13.458 | 0.488 15 | 0.71 | 0.206 | 1.5 | ASAS 185038+4125.4 | Q0, Q1, Q2 | |
| 6183128 | 18 52 50.36 | +41 33 49.46 | 16.260 | 0.561 68 | 1.07 | 0.245 | 1.9 | V354 Lyr | Q1, Q2 | Bl, n |
| 6186029 | 18 58 25.69 | +41 35 49.45 | 17.401 | 0.512 93 | 1.13 | 0.204 | 2.0 | V445 Lyr | Q1, Q2 | Bl, n |
| 6763132 | 19 07 48.37 | +42 17 54.67 | 13.075 | 0.587 79 | 1.13 | 0.280 | 2.3 | NQ Lyr | Q0, Q1, Q2 | |
| 7030715 | 19 23 24.53 | +42 31 42.35 | 13.452 | 0.683 62 | 1.43 | 0.231 | 1.8 | ASAS 192325+4231.7 | Q0, Q1, Q2 | |
| 7176080 | 18 49 24.43 | +42 44 45.56 | 17.433 | 0.507 08 | 0.94 | 0.357 | 3.0 | V349 Lyr | Q1, Q2 | Bl, n |
| 7198959 | 19 25 27.91 | +42 47 03.73 | 7.862 | 0.566 88 | 1.26 | 0.239 | 2.2 | RR Lyr | Q1, Q2 | Bl |
| 7505345 | 18 53 25.90 | +43 09 16.45 | 14.080 | 0.473 70 | 1.29 | 0.374 | 3.4 | V355 Lyr | Q2 | Bl |
| 7671081 | 19 09 36.63 | +43 21 49.97 | 16.653 | 0.504 57 | 0.86 | 0.313 | 2.5 | V450 Lyr | Q1, Q2 | Bl |
| 7742534 | 19 10 53.40 | +43 24 54.94 | 16.002 | 0.456 49 | 0.77 | 0.407 | 3.5 | V368 Lyr | Q1, Q2 | n |
| 7988343 | 19 59 50.67 | +43 42 15.52 | 14.494 | 0.581 15 | 1.28 | 0.341 | 3.0 | V1510 Cyg | Q1, Q2 | |
| 8344381 | 18 46 08.64 | +44 23 13.99 | 16.421 | 0.576 83 | 1.26 | 0.322 | 2.9 | V346 Lyr | Q1, Q2 | |
| 9001926 | 18 52 01.80 | +45 18 31.61 | 16.914 | 0.556 82 | 1.13 | 0.287 | 2.5 | V353 Lyr | Q1, Q2 | Bl, n |
| 9508655 | 18 49 08.37 | +46 11 54.96 | 15.696 | 0.594 24 | 1.33 | 0.339 | 3.0 | V350 Lyr | Q1, Q2 | |
| 9578833 | 19 09 40.64 | +46 17 18.17 | 16.537 | 0.527 02 | 0.99 | 0.304 | 2.5 | V366 Lyr | Q1, Q2 | Bl, n |
| 9591503 | 19 33 00.91 | +46 14 22.85 | 13.293 | 0.571 39 | 1.09 | 0.384 | 3.2 | V894 Cyg | Q0, Q1, Q2 | |
| 9697825 | 19 01 58.63 | +46 26 45.74 | 16.265 | 0.557 59 | 1.06 | 0.261 | 2.1 | V360 Lyr | Q1, Q2 | Bl, n |
| 9947026 | 19 19 57.96 | +46 53 21.41 | 13.300 | 0.548 59 | 0.88 | 0.219 | 1.6 | V2470 Cyg | Q0, Q1, Q2 | |
| 10136240 | 19 19 45.28 | +47 06 04.43 | 15.648 | 0.565 79 | 1.23 | 0.270 | 2.4 | V1107 Cyg | Q1, Q2 | n |
| 10789273 | 19 14 03.90 | +48 11 58.60 | 13.770 | 0.480 29 | 0.86 | 0.390 | 3.4 | V838 Cyg | Q1, Q2 | |
| 11125706 | 19 00 58.77 | +48 44 42.29 | 11.367 | 0.613 23 | 0.98 | 0.179 | 1.2 | ROTSE1 J190058.77+484441.5 | Q0, Q1, Q2 | Bl |
| 12155928 | 19 18 00.49 | +50 45 17.93 | 15.033 | 0.436 39 | 0.71 | 0.394 | 3.4 | V1104 Cyg | Q1, Q2 | Bl |

29 RR Lyrae stars were observed in this way. One additional RR Lyrae star (V355 Lyr) has been released since the publication by Kolenberg et al. (2010a). This source was observed as a Director's Discretionary Target[1] in the *Kepler* Guest Observer Programme from quarter 2 onwards, and is included here to enrich the KASC sample. Throughout this paper, we used only the long-cadence data.[2]

The commissioning phase data (Q0) included six of the RR Lyrae stars between 2009 May 2 and 11 (9.7 d), the observations of Q1 data began on 2009 May 13 and ended on 2009 June 15 (33.5 d). The first full quarter of data (Q2) ran from 2009 June 19 to 2009 September 16 (89 d). At present, the combined number of data points for a given star is between 4096 and 6175. Column 8 in Table 1 shows the available data sets for each star.[3]

The telescope is rotated by 90° four times per orbital period for best exposure of the solar panels. Accordingly, the Q0 and Q1 data sets were observed at one position and the first roll was executed between Q1 and Q2. The different apertures applied to a given star in the two positions caused the zero-points of the raw fluxes and the amplitudes of a star to be different for the two rolls. We applied simple linear transformations to fit the amplitudes and zero-points for combining the data. The long time-scale trends were removed from the raw fluxes by a trend-filtering algorithm prepared for *CoRoT* RR Lyrae data (Chadid et al. 2010),[4] then fluxes were transformed into a magnitude scale, where the averaged magnitude of each star was fixed to zero. Measured raw fluxes are in the range of $3.1 \times 10^{10} > F > 1.3 \times 10^6$ analogue-to-digital units (ADU) which yields $6 \times 10^{-6}$ to $9 \times 10^{-4}$ mag accuracy for an individual data point.

## 3 ANALYSIS AND RESULTS

As a first step Fourier analyses were performed on the data sets. To this end we used the software packages MUFRAN (Kolláth 1990), PERIOD04 (Lenz & Breger 2005) and SIGSPEC (Reegen 2007), all of which gave similar frequency spectra with similar errors. Some basic parameters of the observed stars are summarized in Table 1. The columns of the table show the ID numbers, J 2000 positions (RA, Dec.) and apparent magnitude (*Kepler* magnitude $K_p$), all from the *Kepler* Input Catalogue (KIC-10).[5] The next columns contain the main pulsation periods and the Fourier amplitude of the main frequencies obtained from our SIGSPEC analysis. These two basic parameters ($P_0$ and $A_1$) were previously unknown or wrong for nine stars (signed by an 'n' in the last column).

This fact already suggests that there were hardly any detailed investigations on these stars before this work. This is underlined by the lack of known stars showing Blazhko effect before *Kepler* except RR Lyr itself. In most of the cases these stars are

[1] http://keplergo.arc.nasa.gov/GOprogramDDT.shtml

[2] We have observed several additional RR Lyrae candidates with short cadence (1-min integration); results from these data will be discussed in a forthcoming paper.

[3] Public *Kepler* data can be downloaded from the web page http://archive.stsci.edu/kepler/.

[4] http://www.konkoly.hu/HAG/Science/index.html

[5] http://archive.stsci.edu/kepler/kic10/search.php

mentioned in the literature apropos of their discoveries and in some cases due to the determination of their position and/or ephemeris. The radial velocity measurements of NR Lyr and V894 Cyg were used for kinematic study of the Galaxy (Layden 1994; Beers et al. 2000; Jeffery et al. 2007). The Northern Sky Variability Survey (NSVS) included NR Lyr, V355 Lyr and V2470 Cyg. Their NSVS light curves – together with more than 1100 other ones – formed the basis of the statistical study of Kinemuchi et al. (2006). The most specific investigations were carried out on V783 Cyg by Loser (1979) and Cross (1991), who found a period increase between 1933 and 1990 with the ephemeris of $\mathrm{JD_{max}} = 243\,6394.332 + 0.620\,696\,69E + 7.5 \times 10^{-11}E^2$. According to Table 1 the period is still increasing with a good agreement of the rate of Cross's value: $0.088 \pm 0.023\,\mathrm{d\,Myr^{-1}}$.

The standard errors of the main period and amplitude (in columns 6 and 8) were estimated from the accuracy of non-linear least-squares fits. The last three columns of the table indicate other identifications of the stars, the observing runs analysed and the presence of a Blazhko effect, respectively. All the periods, amplitudes and light-curve shapes of the 29 stars are typical for RRab stars pulsating in their radial fundamental mode; therefore, these classifications are omitted from Table 1.

### 3.1 RR Lyrae stars with amplitude modulation

Generally, it is an easy task to distinguish amplitude modulated and non-modulated *Kepler* RR Lyrae light curves. A gallery of modulated light curves is shown in Fig. 1. It is obvious at first glance that the modulation cycles are predominantly long and the amplitude of the effect is clearly visible. Non-sinusoidal envelopes of the light curves (see e.g. V2178 Cyg, KIC 3864443) or moving bumps (e.g. V366 Lyr, KIC 9578833) are also conspicuous.

The interesting light curve of V445 Lyr (KIC 6186029) is shown separately in Fig. 2. The two observed Blazhko cycles are surprisingly different. The high amplitude of the Blazhko modulation extremely distorts the shape of the light curve. This is demonstrated in the small panels of Fig. 2. Signs of complex variations are detectable from the Fourier spectrum as well. The spectrum of the data pre-whitened with the main pulsation frequency and its harmonics shows four peaks around each of the harmonics (Fig. 3). Two outer peaks at the harmonics can be identified as elements of the Blazhko triplets ($f_0 \pm f_\mathrm{B}$). Two other side peaks closer to the harmonic frequencies show the possible variation of the Blazhko effect on a time-scale longer than the observation run. This may be a result of a cyclic variation (existence of more than one Blazhko modulation), a secular trend or random changes. Several papers have reported multiperiodic and/or unstable behaviours in the Blazhko effect (e.g. LaCluyzé et al. 2004; Collinge, Sumi & Fabrycky 2006; Kolenberg et al. 2006; Nagy & Kovács 2006; Sódor et al. 2006; Szczygieł & Fabrycky 2007; Wils, Kleidis & Broens 2008; Jurcsik et al. 2009c). After investigating the two Blazhko cycles noted here, we are not in the position to decide on the nature of this variation, but the 3.5–5 yr long time base of *Kepler*'s observations will provide an excellent opportunity to study this strange behaviour.

We were systematically searching for low-amplitude Blazhko RR Lyrae stars. Instrumental trends of the observed fluxes that are not properly removed could cause apparent amplitude changes in the non-linear magnitude scale. A decreasing trend of the averaged fluxes results in increasing amplitudes in magnitudes and vice versa. Therefore, we always checked the amplitude variation using the raw fluxes. We divided the data sets into small sections (typically 2–3 d in length), then calculated the amplitude difference $\delta A_1(t)$ of the first Fourier component and its averaged value $\Delta A_1$ over the whole time-span for all sections by a non-linear fit. These calculated functions reflect well the variation of pulsation amplitude seen in the light curves.

With the help of this tool we found in KIC 11125706 the lowest amplitude modulation ever detected in an RR Lyrae star. Full amplitude of the maximum light variation $A(K_\mathrm{p})_\mathrm{max} = 0.015$ mag and the amplitude of the highest side peak in the Fourier spectrum



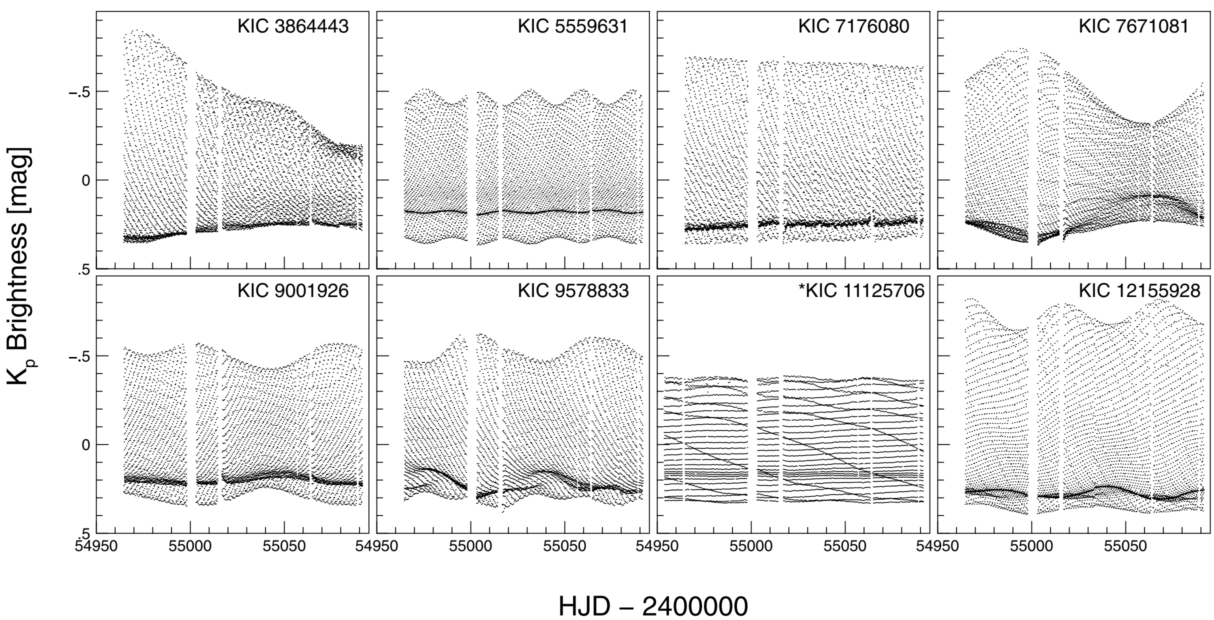


**Figure 1.** The gallery of *Kepler* Blazhko stars. The figure shows the complete light curves of eight stars observed with long cadence during the periods Q0 through Q2. Further light curves are given in Figs 2 and 5 and in our parallel papers (Szabó et al. 2010; Kolenberg et al. 2010b). Lines seen running through these light curves are visual artefacts caused by beating of the sampling frequency with the pulsation frequencies. They cause no problems in the Fourier analysis. *For better visibility the scale of KIC 11125706 is increased by a factor of 1.5.

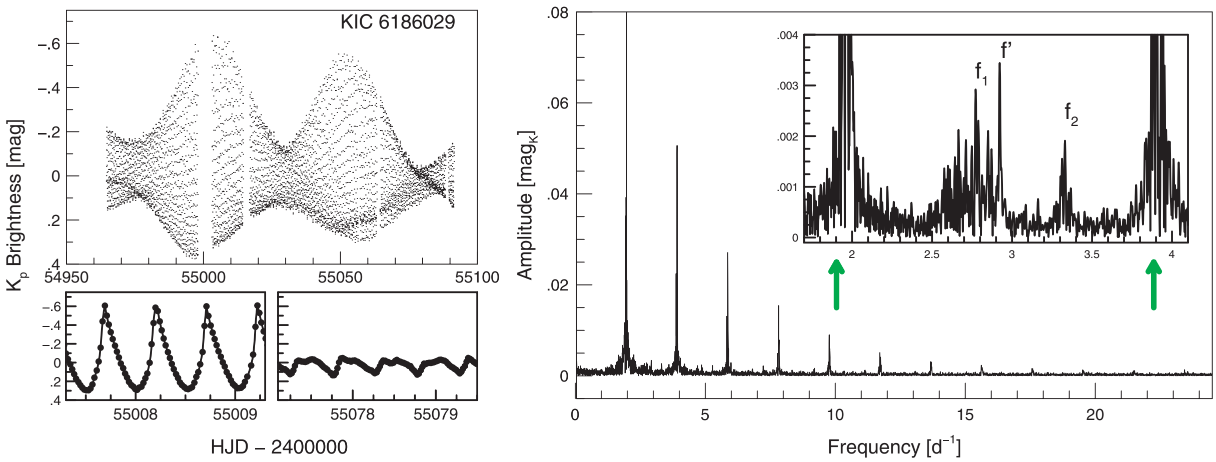


**Figure 2.** Top left-hand panel: light curve of V445 Lyr (KIC 6186029). Bottom left-hand panel: parts of the light curve from maximum and minimum of the amplitude of the Blazhko cycle. Right-hand panel: Fourier spectrum after the data are pre-whitened with the main frequency and its harmonics. The insert is a zoom around the positions of the main frequency $f_0$ and its first harmonics $2f_0$ (showed by green arrows) after the 20 highest amplitude frequencies were removed. The complex structure of additional frequencies is clearly seen.

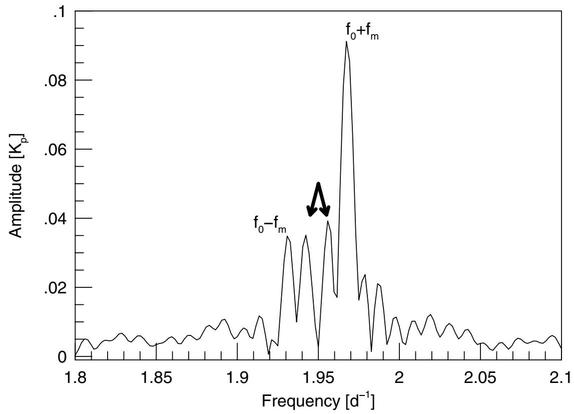


**Figure 3.** Fourier amplitude spectrum of V445 Lyr (KIC 6186029) around the main pulsation frequency $f_0$ after the data are pre-whitened with the main frequency. Beyond elements of the Blazhko triplet $f_0 \pm f_B$ two additional peaks are seen (arrows).

is only $A_{K_p}(f_0 + f_B) = 0.0022$ mag. The lowest published amplitude of a Blazhko effect previously found was the case of DM Cyg (Jurcsik et al. 2009b), where $A(V)_{max} = 0.07$ mag, $A_V(f_0 + f_B) = 0.0096$ mag and $A_I(f_0 + f_B) = 0.0061$ mag. The two measurements are not strictly comparable because *Kepler* passband is broad in white light. However, the maximum of its spectral response function (see Koch et al. 2010) is about 6000 Å between Johnson–Cousins filters $V$ and $R$.

All the Blazhko RR Lyrae stars found in our sample are listed in Table 2. The estimated lengths of the Blazhko cycles are indicated in the third column. For the shorter periods than the total time-span they were calculated from the averaged frequency differences of the highest side peaks ($f_0 + f_B$ and $f_0 - f_B$), otherwise a minimum period is given. The fourth column shows the amplitude modulation parameter $\Delta A_1$ defined above.

We note here, the triplet structure has always appeared for all Blazhko stars, i.e. no stars show frequency doublets. The amplitude of the high-frequency peak is higher than the lower for nine stars. The remaining five show the opposite pattern. The asymmetry parameter $Q$ defined by Alcock et al. (2003) as $Q = [A(f_0 + f_B) - A(f_0 - f_B)]\ [A(f_0 + f_B) + A(f_0 - f_B)]^{-1}$ varies from $-0.251$ to 0.676 (see the sixth column in Table 2); however, these values are rather preliminary due to the long Blazhko cycles.

In the past few years, thanks to high-precision ground- and space-based observations, the known occurrence rate of the Blazhko effect among RR Lyrae stars has increased from the former estimate of 15–30 per cent to a ratio close to 50 per cent (see Chadid et al. 2009; Jurcsik et al. 2009c; Kolenberg et al. 2010a). It is even possible that all RR Lyrae stars may show a Blazhko modulation with an increasing frequency of Blazhko stars at lower modulation amplitude. The *Kepler* measurements provide an ideal tool to test this hypothesis. From our $\Delta A_1$ values in Table 2 it can be seen that we found only two stars with modulation amplitude lower than 0.1 mag.

To test our detection limit of the amplitude modulation, artificial light curves were generated. Two sets of grids were constructed: one for V368 Lyr (KIC 7742534) and another for KIC 7030715. These stars have the shortest and the longest pulsation periods (0.456 49 and 0.682 04 d) in the sample, respectively. In both cases the Fourier parameters of the main pulsation frequency and its significant harmonics were used to build the artificial light curves. These were modulated by a simple sinusoidal function with amplitudes ranging between 0.1 and 0.001 mag, and with modulation periods from 25 to 150 d with a step size of 25 d, according to the general modulation formula (equation 2) in Benkő et al. (2009). Measured averaged fluxes of the non-Blazhko stars are in the range of $1.8 \times 10^8 > F > 2.7 \times 10^6$ ADU which means a noise between $8 \times 10^{-5}$ and $6 \times 10^{-4}$ mag. This was taken into account by adding Gaussian noise with $\sigma = 10^{-4}$ and $5 \times 10^{-4}$ to the artificial data. The light curves were always calculated at the observed points of time.

In our tests, we reckoned the amplitude modulation as detectable if the highest Fourier side peak connected to the modulation exceeds the spectral significance ($\sigma_s$) 5. [For the definition of the $\sigma_s$ we refer Reegen (2007); the correspondence between more popular amplitude signal-to-noise ratio (S/N) (Breger et al. 1993) and $\sigma_s$ is yielded as $\sigma_s = 5 \approx$ S/N = 3.83.] The obtained limiting values are $A(f_0 + f_B) > 0.001$–0.002 mag (or $\Delta A_1 > 0.005$–0.01 mag) depending on the brightness, but highly independent of the periods ($P_0$ and $P_B$). Higher sampling rate (i.e. short cadence) does not

**Table 2.** Period, amplitude and phase properties of the Blazhko stars.

| KIC | GCVS | $P_B$ (d) | $\sigma(P_B)$ (d) | $\Delta A_1$ (mag) | $\Delta\phi_1$ | $Q$ | Addition. freq.[a] |
|---|---|---|---|---|---|---|---|
| 3864443 | V2178 Cyg | >200 | | >0.488 | >0.0014 | 0.153 | F2, (PD) |
| 4484128 | V808 Cyg | ≈90 | | 0.304 | 0.012 142 | −0.045 | PD |
| 5559631 | V783 Cyg | 27.7 | 0.4 | 0.071 | 0.001 591 | 0.156 | |
| 6183128 | V354 Lyr | ≫127 | | >0.245 | >0.002 45 | −0.139 | F2, (F1, PD, F′) |
| 6186029 | V445 Lyr | 53.2[b] | 2.8 | 0.968 | 0.022 442 | 0.540 | PD, F1, F2 |
| 7176080 | V349 Lyr | ≫127 | | >0.060 | >0.001 75 | −0.251 | |
| 7198959 | RR Lyr | 39.6 | 1.8 | 0.461 | 0.013 836 | 0.676 | PD |
| 7505345 | V355 Lyr | 31.4 | 0.1 | 0.107 | 0.003 518 | 0.136 | PD |
| 7671081 | V450 Lyr | ≈125 | | 0.391 | 0.004 882 | 0.235 | |
| 9001926 | V353 Lyr | 60.0 | 7.1 | 0.157 | 0.004 026 | 0.033 | |
| 9578833 | V366 Lyr | 65.6 | 2.6 | 0.171 | 0.003 205 | −0.162 | |
| 9697825 | V360 Lyr | 51.4 | 4.3 | 0.356 | 0.008 228 | 0.279 | F1, (PD) |
| 11125706 | | 39.4 | 2.0 | 0.030 | 0.001 420 | 0.540 | |
| 12155928 | V1104 Cyg | 53.1 | 0.3 | 0.105 | 0.002 451 | −0.063 | |

[a]The pattern of additional frequencies: PD means period doubling; F1 indicates first overtone frequency and its linear combination with fundamental one; F2 is as F1, but with second overtone; F′ indicates frequencies with unidentified modes; brackets indicate marginal effects.
[b]The star shows a longer time-scale variation than its Blazhko modulation as well.

decrease our detection limit because the present sampling frequency 48.98 d$^{-1}$ is much higher than a typical Blazhko frequency (0.1–0.01 d$^{-1}$); hence each Blazhko cycle is covered sufficiently.

Notwithstanding our efforts, we did not detect any modulation for 15 RR Lyrae stars in our *Kepler* sample; however, some very small amplitude modulation with long period might remain undetected.

Using the same number (14) of Blazhko stars Jurcsik et al. (2009c) found an exponential-like distribution of their modulation amplitude strengths. Our sample shows a similar behaviour (top in Fig. 4) when we divide it up into the same 0.025 mag size of bins as were used by Jurcsik et al. (2009c). However, the distribution seems to be more uniform, when we split our sample into smaller size of bins (bottom in Fig. 4). Although, our sample is affected by small number statistics in this respect, we checked the uniformity of the modulation amplitude distribution. We carried out a one-sample Kolmogorov–Smirnov (KS) test over the intervals of (0, $\Delta A_1^{\max}$) and (0, $A(f_0+f_B)^{\max}$), respectively. (The extremely modulated star V445 Lyr was omitted from the sample.) Both tests allowed the uniform distribution hypothesis with 99 per cent of probabilities. We note that the KS test uses data directly, without any binning.

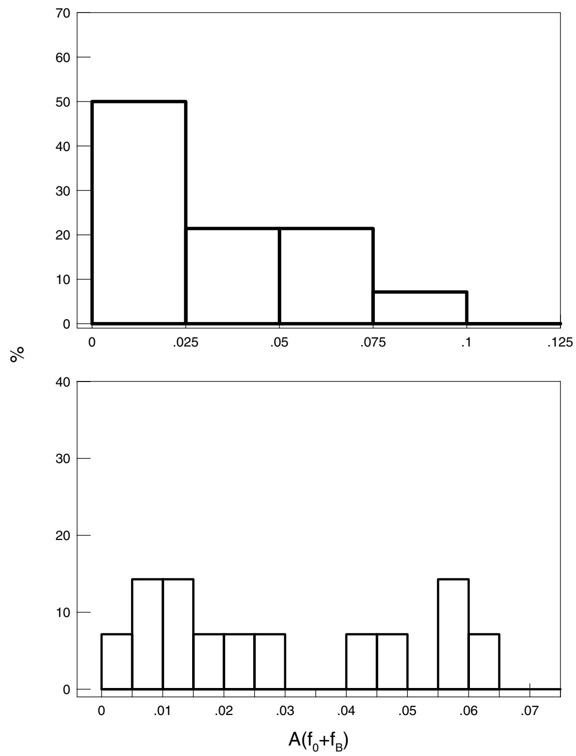


**Figure 4.** Modulation amplitude distribution of the Blazhko variables in the *Kepler* sample using 0.025 mag (top) and 0.005 mag (bottom) size of bins. The modulation amplitude corresponds to the Fourier amplitude of the largest amplitude modulation frequency component $A(f_0+f_B)$.

### 3.2 Phase modulation

Without any ‘a priori’ knowledge about the nature of the modulation, frequency modulation (period changes over the Blazhko cycle) and phase modulation cannot be distinguished: a detected phase variation indicates period changes, and vice versa. From now on we refer to this phenomenon as phase modulation.

We searched for phase modulation in all of our RR Lyrae stars in the same way as was described in the case of amplitude modulation. We calculated the $\Delta\varphi_1$ values from the phase variation function $\delta\varphi_1(t)$. We expressed the phase differences relative to the total cycle, that is $\Delta\phi_1 = \Delta\varphi_1/2\pi$ $(= \delta P_0/P_0)$. The results can be seen in the fifth column of Table 2.

We detected clear phase modulation for all the studied Blazhko RR Lyrae stars. The hardest task was to find it in the case of V2178 Cyg, where the Blazhko cycle is longer than the data set and the phase variation during the observed time-span was only 0.0014 (≈1 min). The reality of this small phase variation was checked and confirmed by the sensitive analytical function method (Kolláth et al. 2002). We can detect period variations smaller than 1.5 min for three further stars: V783 Cyg (KIC 5559631), V349 Cyg (KIC 7176080) and KIC 1125706. The other extremity is represented by V445 Lyr and RR Lyr itself with their values of 0.0224 (= 16.6 min) and 0.0138 (= 11.3 min), respectively. There is no clear indication for any connections between the strengths of the two type of modulations.

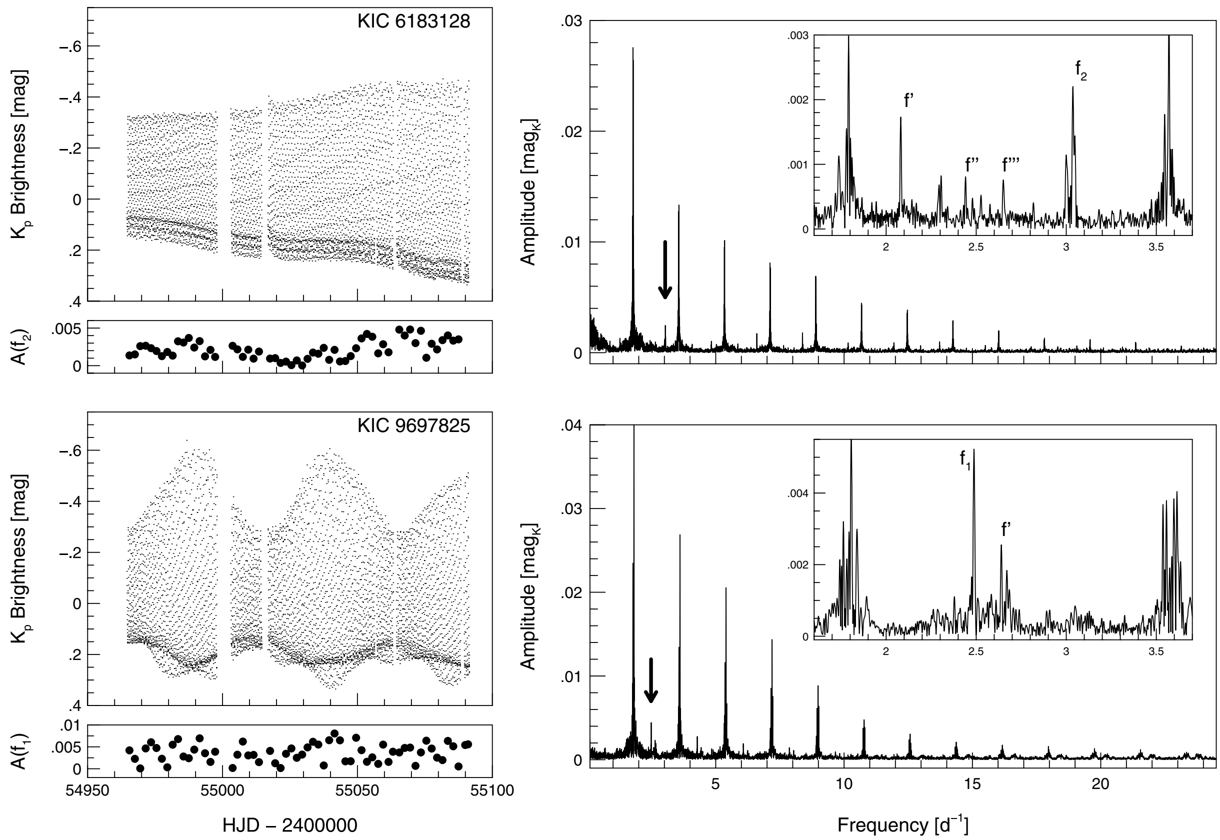


**Figure 5.** Left-hand top panel: light curves of two *Kepler* RR Lyrae stars, V354 Lyr (KIC 6183128) and V360 Lyr (KIC 9697825). Right-hand panel: Fourier spectra after the data are pre-whitened with the main frequency and its harmonics. Arrows point to the highest peaks connected to additional frequencies. The inserts are a zoom around the position of the highest additional peaks. Left-hand bottom panel: amplitude of the highest additional peaks versus time. The typical error is about 0.001 mag – smaller than the size of the data points.

As was shown by Szeidl & Jurcsik (2009) and Benkő et al. (2009), phase modulation always causes multiplet structures of higher order than triplets in the Fourier spectrum around the main frequency and its harmonics. These multiplet peaks were most clearly detected for V808 Cyg, RR Lyr and V360 Lyr, the Blazhko stars with the strongest phase modulation in our sample.

The precise and almost continuous observation of 14 Blazhko RR Lyrae stars measured by *Kepler* convincingly demonstrates that in all Blazhko stars both amplitude and phase variations are present.

### 3.3 Additional frequencies

Besides the modulation components that occur in multiplet structures around the main frequency and its harmonics, we found additional frequencies. In the cases of V808 Cyg, V355 Lyr and RR Lyr these frequencies are located around $f_0/2,\ 3f_0/2,\ 5f_0/2,\ \ldots,$ where $f_0$ denotes the main pulsation frequency. This very interesting period-doubling effect has already been discussed briefly in Kolenberg et al. (2010a) for RR Lyr itself, and a separate paper (Szabó et al. 2010) is dedicated to it. Here we just remark that the presence of these frequencies in the spectra seems to be variable in time and connected to particular Blazhko phases. The phenomenon can be described in a purely radial framework of pulsation theory.

Similarly, time-dependent phenomena might also be important for the four further stars V354 Lyr, V2178 Cyg, V360 Lyr and V445 Lyr, where we discovered additional frequencies with small amplitudes. The light curves of V354 Lyr and V360 Lyr are plotted in the top left-hand panels of Fig. 5. The last column of Table 2 indicates the possible identification of the additional frequencies.

In the Fourier spectrum of *V354 Lyr* (KIC 6183128) the highest ($\sigma_{\rm s} = 34.4$) additional peak is at $f_2 = 3.0369 \pm 0.0002\,{\rm d}^{-1}$ (see insert in Fig. 5). Its ratio to the fundamental frequency ($f_0 = 1.780\,37 \pm 0.000\,04\,{\rm d}^{-1}$) is 0.586, which is close to the canonical ratio of the fundamental and second radial overtone modes. Furthermore, many linear combinations in the form $kf_0 \pm f_2,\ k = 0,\ 1,\ 2,\ \ldots$ are present in the spectrum. As the period-doubling effect has a time-dependent nature, we have checked whether the mode connected to $f_2$ is also temporally excited or not. We tested this possibility both with the analytical function method and the amplitude variation tool of PERIOD04. These two independent methods yielded very similar results and showed the amplitude of $f_2$ changing over the Blazhko cycle (see the plot below the light curve of V354 Lyr in Fig. 5). This means that V354 Lyr is a double-mode pulsator with Blazhko effect, but not in a traditional sense.

The observed frequencies $f_0$ and $f_2$ can be easily matched by the fundamental and second overtone modes in linear pulsation models (Fig. 6). We used the Florida–Budapest code (Yecko, Kolláth & Buchler 1998; Kolláth et al. 2002) to fit the observed frequencies by the theoretical fundamental and second overtones. The model frequencies depend on four parameters, the mass, luminosity, effective temperature and chemical composition. Fixing two frequencies reduces the unknown parameters by two. Then for given chemical composition and effective temperature the mass and luminosity of the matching star can be determined by numerical model

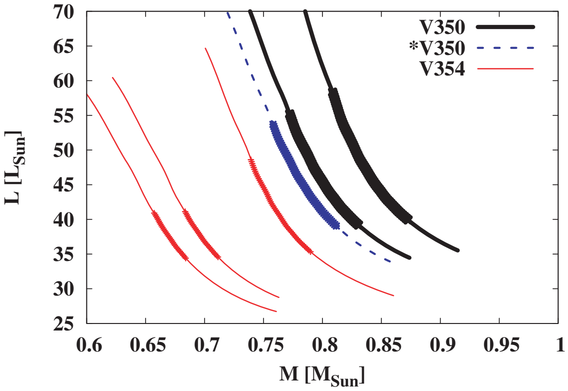


**Figure 6.** Linear pulsation models of V350 Lyr and V354 Lyr. The observed frequencies were fitted with the theoretical fundamental and second overtone modes. The lines represent the mass–luminosity values of the models which exactly fit the observations. Thin (red) lines: V354 Lyr periods with metallicities (left- to right-hand side): $Z = 0.0001, 0.0003, 0.001$; thick (black) lines: V350 Lyr periods with metallicities (left- to right-hand side): $Z = 0.0001, 0.0003$; dashed (blue) line: V350 Lyr periods with $Z = 0.0001$ and the period ratio decreased by 0.001 to show the effect of possible non-linear period shifts. The thicker parts of the curves indicate the parameter range where the second overtone is linearly unstable.

calculations. The resulting mass–luminosity pairs are displayed in Fig. 6. In the figure the linear instability region of the second overtone is also displayed. We have to note, however, that the width of these regions strongly depends on turbulent/convective parameters, and in addition, the linear instability alone is not a sufficient condition for double-mode pulsation. The coexistence of the fundamental and second overtone modes in non-linear pulsation is a new enigma that further theoretical studies should follow.

The frequencies $f'(2.0810 \pm 0.0002\,\mathrm{d}^{-1}; \sigma_s = 28.1)$, $f''(2.4407 \pm 0.0003\,\mathrm{d}^{-1}; \sigma_s = 11.6)$ and $f'''(2.6513 \pm 0.0003\,\mathrm{d}^{-1}; \sigma_s = 10.8$, insert in Fig. 5) are more difficult to identify. Their linear combinations with $f_0$ and its harmonics also appear in the spectrum and ratios are $f_0/f' = 0.855$, $f_0/f'' = 0.729$ and $f_0/f''' = 0.672$. The last two ratios permit an explanation as a first overtone ($f'' = f_1$) and a period-doubled ($f''' = 3f_0/2$) frequency, respectively. However, $f'$ does not seem to fit this picture. This frequency might be connected to a non-radial mode.

The star *V2178 Cyg* (KIC 3864443) shows a similar, but simpler and a bit less significant, additional peaks than V354 Lyr. In this case the highest peak can be found again at the second overtone frequency $f_2$ $(3.5089 \pm 0.0002\,\mathrm{d}^{-1}; \sigma_s = 15.8)$. One further peak at $f' = 3.0585 \pm 0.0003\,\mathrm{d}^{-1}$ $(\sigma_s = 9.8)$ was detected that might be a sign of a marginal period-doubling effect $(3f_0/2)$.

The other star where we found highly significant additional frequencies is *V360 Lyr* (KIC 9697825). The dominating extra peak in its spectrum is located at $f_1 = 2.4875 \pm 0.0001\,\mathrm{d}^{-1}$ with $\sigma_s = 51.9$ (bottom right-hand panel in Fig. 5). The ratio of this frequency to the fundamental mode frequency ($f_0 = 1.793\,44 \pm 0.000\,03\,\mathrm{d}^{-1}$) is 0.721. This value is a bit smaller than the generally accepted ratio of fundamental to first radial overtone frequencies ($f_1/f_0 = 0.745$), but some model calculations with higher metallicity (see fig. 8 in Chadid et al. 2010) allow double-mode pulsation with this ratio as well. We also detect a low-amplitude, but significant ($\sigma_s = 18.9$), peak at the frequency of $f' = 2.6395 \pm 0.0002\,\mathrm{d}^{-1}$. Its ratio $f_0/f' = 0.679$ is almost the same as was found for V1127 Aql, a Blazhko RR Lyrae star observed with *CoRoT* and explained there by a non-radial pulsation mode (Chadid et al. 2010) .

*V445 Lyr* (KIC 6186029) has a very complex structure of frequencies at the low-amplitude level (see right-hand panel in Fig. 2). Here, the three types of frequency patterns (connected to the first and second overtone modes and period-doubling effect) show similarly significant peaks. In decreasing order of amplitude, $3f_0/2 = 2.9231 \pm 0.0002\,\mathrm{d}^{-1}$ $(\sigma_s = 24.5)$, $f_1 = 2.7725 \pm 0.0002\,\mathrm{d}^{-1}$ $(\sigma_s = 21.1)$ and $f_2 = 3.331\,549 \pm 0.0002\,\mathrm{d}^{-1}$ $(\sigma_s = 13.5)$.

If the global physical parameters are varying over the Blazhko cycle as demonstrated by Jurcsik et al. (2009a,b) excitation of a radial (or may be a non-radial) mode temporally (when the physical conditions of excitation are realized) would be a natural explanation for these patterns.

The frequency spectra of non-Blazhko stars were checked to see whether any of them possesses additional frequencies. This search resulted in the discovery the double-mode nature of *V350 Lyr* (KIC 9508655). Its Fourier spectrum (see Fig. 7) contains a significant ($\sigma_s = 11.5$) peak at $f_2 = 2.8402 \pm 0.0003\,\mathrm{d}^{-1}$ with the amplitude of $A(f_2) = 0.001$ mag. The ratio of this frequency to the fundamental mode frequency ($1.682\,814 \pm 0.000\,03\,\mathrm{d}^{-1}$) is 0.592. That is, V350 Lyr is the first example of a non-Blazhko double-mode RR Lyrae star, where the fundamental and second overtone modes are excited. The extremely high-amplitude ratio, $A(f_0)/A(f_2) = 316$, points out why we have not been able to find such stars from the ground.

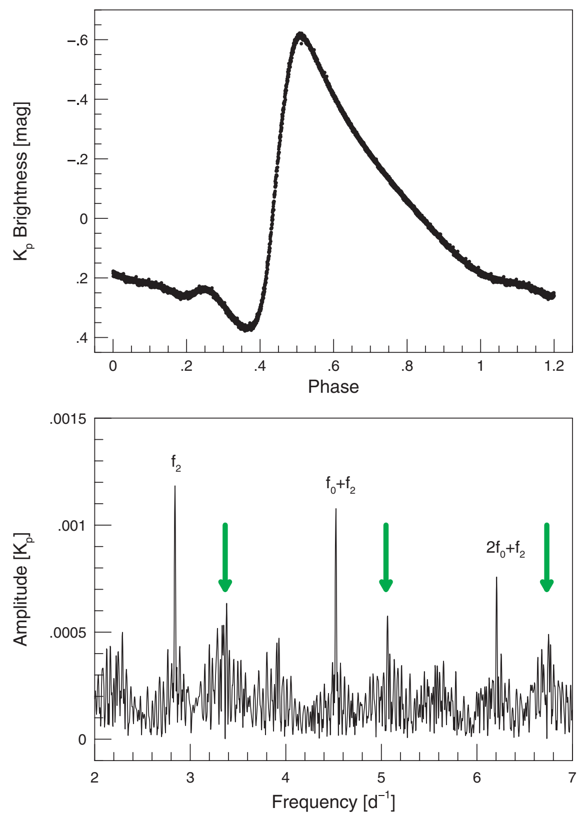


**Figure 7.** Top: phase diagram of V350 Lyr (KIC 9508655). The *Kepler* light curve is folded by the main period of $P_0 = 0.594\,24$ d. Bottom: Fourier amplitude spectrum of V350 Lyr around the highest peaks after the data were pre-whitened with the main frequency $f_0$ and its harmonics. Due to small instrumental trends some residuals are seen at the location of removed harmonics (shown by green arrows).

The residual peaks around the main frequency and its harmonics raise the possibility of the presence of the Blazhko effect close to the detection limit. However, neither the $A_1(t)$ function nor the amplitude of the overtone frequency shows clear time variation. In the future, calibrated *Kepler* data gathered over a longer time-span may clarify the nature of this interesting object.

In the case of V350 Lyr, the match of the observed frequencies to the theoretical model is a tougher problem than the case of V354 Lyr. High mass or luminosity is required to fit the empirical data even at low metallicity (Fig. 6). However, a small shift in the period ratio results in a better agreement with the canonical mass and luminosity values. 0.001 difference in the observed period ratio and the linear model values can be accounted to observational errors and non-linear effects of stellar pulsations.

## 4 SUMMARY

In this paper we have outlined some results obtained for RR Lyrae stars based on the first 138-d long data sets of the *Kepler Mission*.

(i) We have determined the main pulsation periods and amplitudes for all stars in this sample. These parameters were previously unknown or wrong for nine stars.

(ii) We have found 14 certain Blazhko stars among the 29 stars of the observed sample (48 per cent), and we could not find any deviations from monoperiodicity for 15 stars (52 per cent). Statistical distribution of the measured modulation amplitudes proved to be highly dependent on the used size of bins. Our sample supports the uniform distribution.

(iii) The possibility of multiple modulations of an RR Lyrae star is well known, such as the 4-yr cycle of RR Lyr itself. Further secondary modulation cycles were also reported in the literature. We found a long-term variation of the Blazhko cycle in V445 Lyr. The forthcoming long time base of the *Kepler* data will allow us to investigate this phenomenon in detail.

(iv) The *Kepler* data made it possible to find the Blazhko modulation of KIC 1125706 with an amplitude as small as 0.03 mag. This is by far the smallest modulation amplitude ever detected for a Blazhko star. The same is true for phase modulations: we found small but clear phase variations for stars V2178 Cyg, V783 Cyg, V349 Cyg and KIC 1125 706. For these cases the $\delta P_0 < 1.5$ min period variation again have the smallest known values.

(v) The sensitivity both in amplitude and phase made it possible to detect phase variation for all Blazhko stars. Although our sample is small, it is notable that all of our Blazhko stars are modulated both in their amplitude and phase simultaneously. The relative strength of the two types of modulation varies from star to star, but always has a common period. Therefore, a plausible explanation for the Blazhko effect must account for both amplitude and phase variations.

(vi) We found additional frequencies, beyond the main frequency, its harmonics and expected modulation components, in the Fourier spectra of seven Blazhko-type stars. These additional frequencies concentrate around $f_0/2,\ 3f_0/2,\ \ldots$ for three stars, while they appear around the first and second overtone frequency and its linear combination with the harmonics of the main frequency in the the case of V354 Lyr, V2178 Cyg and V360 Lyr, respectively. A special case is V445 Lyr where all of the above-mentioned types of frequencies are present.

If the basic physical parameters, such as mean radius, luminosity, effective temperature, are varying over the Blazhko cycle, a radial (or may be non-radial) mode could be excited temporally. This would be a natural explanation for these transients.

(vii) As a by-product of our frequency search for additional frequencies, we may have found the first double-mode RR Lyrae star, V350 Lyr, which pulsates in its fundamental and second overtone mode simultaneously.

Comprehensive and more detailed study of the increasing *Kepler* RR Lyrae data sets are in progress and will be discussed in the near future.

## ACKNOWLEDGMENTS

Funding for this *Discovery* mission is provided by NASA's Science Mission Directorate. This project has been supported by the National Office for Research and Technology through the Hungarian Space Office Grant No. URK09350 and the 'Lendület' programme of the Hungarian Academy of Sciences. KK acknowledges the support of Austrian FWF projects T359 and P19962. The authors gratefully acknowledge the entire *Kepler* team, whose outstanding efforts have made these results possible.

## REFERENCES

Alcock C. et al., 2003, ApJ, 598, 597
Beers T. C., Chiba M., Yoshii Y., Platais I., Hanson R. B., Fuchs B., Rossi S., 2000, AJ, 119, 2866
Benkő J., Paparó M., Szabó R., Chadid M., Kolenberg K., Poretti E., 2009, in Guzik J. A., Bradley P., eds, AIP Conf. Proc. Vol. 1170, Stellar Pulsation: Challenges for Theory and Observation. Am. Inst. Phys., New York, p. 273
Blazhko S. N., 1907, Astron. Nachrichten, 175, 325
Breger M. et al., 1993, A&A, 271, 482
Chadid M. et al., 2009, in Guzik J. A., Bradley P., eds, AIP Conf. Proc. Vol. 1170, Stellar Pulsation: Challenges for Theory and Observation. Am. Inst. Phys., New York, p. 235
Chadid M. et al., 2010, A&A, 510, A39
Collinge M. J., Sumi T., Fabrycky D., 2006, ApJ, 651, 197
Cross J., 1991, J. American Association Var. Star Obser., 20, 214
Dziembowski W. A., Mizerski T., 2004, Acta Astron., 54, 363
Gilliland R. L. et al., 2010, PASP, 122, 131
Jeffery E. J., Barnes T. G., III, Shillen I., Montemayor T. J., 2007, ApJS, 171, 512
Jenkins J. M. et al., 2010a, ApJ, 713, L87
Jenkins J. M. et al., 2010b, ApJ, 713, L120
Jurcsik J. et al., 2009a, MNRAS, 393, 1553
Jurcsik J. et al., 2009b, MNRAS, 397, 350
Jurcsik J. et al., 2009c, MNRAS, 400, 1006
Kinemuchi K., Smith H. A., Woź niak P. R., McKay T. A., 2006, AJ, 132, 1202
Koch D. G. et al., 2010, ApJ, 713, L79
Kolenberg K. et al., 2006, A&A, 459, 577
Kolenberg K. et al., 2010a, ApJ, 713, L198
Kolenberg K. et al. 2010b, MNRAS, submitted
Kolláth Z., 1990, Occassional Tech. Notes Konkoly Obser. No. 1
Kolláth Z., Buchler J. R., Szabó R., Csubry Z., 2002, A&A, 385, 932
Kovács G., 2009, in Guzik J. A., Bradley P., eds, AIP Conf. Proc. Vol. 1170, Stellar Pulsation: Challenges for Theory and Observation. Am. Inst. Phys., New York, p. 261
LaCluyzé A. et al., 2004, AJ, 127, 1653
Layden A. C., 1994, AJ, 108, 1016
Lenz P., Breger M., 2005, Comm. Asteroseismol., 146, 53
Loser A. R., 1979, J. Am. Assoc. Var. Star Obser., 8, 69
Nagy A., Kovács G., 2006, A&A, 454, 257
Reegen P., 2007, A&A, 467, 1353
Shibahashi H., 2000, in Szabados L., Kurtz D. W., eds, ASP Conf. Ser. Vol. 203, The Impact of Large-Scale Surveys on Pulsating Star Research. Astron. Soc. Pac., San Francisco, p. 299

Sódor Á. et al., 2006, Inf. Bull. Var. Stars, 5705
Stothers R. B., 2006, ApJ, 653, 73,
Szabó R. et al. 2010, MNRAS, submitted
Szczygieł D. M., Fabrycky D. C., MNRAS, 377, 1263
Szeidl B., 1988, in Kovács G., Szabados L., Szeidl B., eds, Multimode Stellar Pulsations. Kultura, Budapest, p. 45
Szeidl B., Jurcsik J., 2009, Comm. Asteroseismol., 160, 17
Wils P., Kleidis S., Broens E., 2008, MNRAS, 387, 783
Yecko P. A., Kolláth Z., Buchler J. R., 1998, A&A, 336, 553

This paper has been typeset from a TEX/LATEX file prepared by the author.